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Land Degradation and Desertification

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CONTENTS

EXECUTIVE SUMMARY

The impact of climate change on soils needs to be considered in parallel with impacts caused by unsustainable land-management practices. In many cases, it is impossible to separate the effects of these impacts; often they interact, leading to a greater cumulative effect on soils than would be predicted from a simple summation of their effects. Findings follow:

- Fundamental soil properties and processes—including organic-matter decomposition, leaching and acidification, salinization, soil water regimes, soil stability, and soil erosion—will be influenced by changes in climate (High Confidence).
- Desertification arises both from human abuse of the land and from adverse climate conditions. Climate-related factors such as increased drought can lead to an increase in the vulnerability of land to desertification and to the escalation of the desertification process (High Confidence).
- Reversing the effects of desertification is not always possible and is more difficult for drier environments with shallower soils (High Confidence).
- Changes in the frequency and intensity of precipitation will have the greatest direct effect on soils via erosion by water. However, future erosion risk is likely to be related more to increases in population density, intensive cultivation of marginal lands, and the use of resource-based and subsistence farming techniques than to changes in precipitation regimes (High Confidence).
- In structurally stable soils, greater precipitation will increase the rate of leaching of basic cations. In the long term, after buffering pools have become exhausted, accelerated leaching could lead to soil acidification (High Confidence).
- Higher temperatures are likely to increase the decomposition rate of organic matter and organic-matter loss (High Confidence). However, too little is known about the influence of increased atmospheric carbon dioxide (CO_2) levels on the amount of organic matter returning to the soil to judge the extent to which soil organic-matter levels will decline.
- Where conditions become more arid, salinization and alkalization are likely to increase because evapotranspiration and capillary rise will be enhanced (High Confidence). Areas with a shallow water table may experience increased salinization if rainfall increases (Medium Confidence).
- Predicted warming may give rise to higher evaporation rates, leading to drier soils and more frequent episodes of severe wind erosion (Medium Confidence).
- Because arid and semi-arid land ecosystems have little ability to buffer the effects of climate variability relative to most other terrestrial ecosystems, they are particularly vulnerable to climate change and may be among the first ecosystems to be affected by global environmental change (Medium Confidence).
- Adaptation to desertification will rely on conventional strategies, such as the use of agroforestry, animals that are better adapted to dry conditions, diverse and multiple production systems, and water- and energy-saving techniques (Medium Confidence).
- Climate change could be beneficial to some semi-arid and sub-humid tropical highlands because of temperature increases and CO_2 fertilization (Medium Confidence).

4.1. Introduction

Land degradation, defined here as "a reduction in the capability of the land to support a particular use" (Blaikie and Brookfield, 1987), is considered to be one of the major problems facing the world (UNEP, 1992). In this chapter, we examine the likely impact of climate change on this global problem. Will degradation of land be exacerbated or reduced? There are many recognized forms of land degradation, including soil erosion, salinization, soil contamination, loss of soil organic matter, decline in nutrient levels, acidification, and loss of soil structure. Desertification currently affects about one-sixth of the world's population and one-quarter of the world's land: 6 to 7 million hectares (Mha) are lost annually due to soil erosion, and up to 20 Mha of irrigated land are affected by salinization (World Resources Institute, 1992). Much of this degradation is undermining economic development and is already irreversible.

With the forecast world population increase, there will be increased pressure on the soil to produce more food; thus, future trends in the potential of land to produce food will be of particular interest. The impact of climate change on the health of the land should be considered in parallel with the effects of existing pressures caused by unsustainable land management—because it is often impossible to separate the effects of these impacts and because their cumulative impact on soils often is greater than a simple summation.

Emphasis in this chapter is given to the effects of climate change on soil erosion, salinization, and desertification, but impacts on other degradation processes capable of being accelerated by climate change also are reviewed. Additional processes of importance include organic-matter loss, nutrient loss, acidification, and soil structural deterioration (Rogasik *et al*., 1994). In some instances, changes in such processes will lead to the formation of new soil types requiring new types of management and having different use potentials.

4.2. Soil Erosion: Causes, Processes, and Predictions

Soil erosion is the movement and transport of soil by various agents—particularly water, wind, and mass movement—that leads to a loss of soil. Erosion has been recognized by many scientists and some governments as a major problem since the U.S. Dust Bowl of the 1930s (Jacks and Whyte, 1939); the causes and processes involved have been well-researched over the last 60 years, providing voluminous literature.

Clearing soils of their natural vegetation cover and subsequently using them for arable agriculture has been the primary cause of soil erosion onset. Historically, this has resulted in disastrous soil losses, particularly in conjunction with climate variations and extreme weather events (Bork, 1983, 1989). More recently, population pressure in developing countries, as well as changes in land use and management in other parts of the world, have increased erosion susceptibility even further.

The annual rates of new soil formation are crudely estimated to be between 2 and 11 t/ha (Wischmeier and Smith, 1978), although experimentally derived rates often are less than this (Lal, 1994a). Globally, rates of soil erosion can exceed these estimated values by 10- to 20-fold, thereby reducing productivity (Crosson and Stout, 1983; Sehgal and Abrol, 1994a, 1994b) and causing sediment and nutrient loading of rivers (Clark *et al*., 1985).

The main factors influencing soil erosion are rainfall (amount, frequency, duration, and intensity), windspeed (direction, strength, and frequency of high-intensity events), land use and management, topography, and soils and their properties (Morgan, 1986; Hallsworth, 1987). Since the 1950s, significant advances have been made in predicting erosion risk, particularly through model development. Several models that are commonly used include the Wind Erosion Equation (Woodruff and Siddoway, 1965), the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978), EPIC (Williams *et al*., 1990; Skidmore and Williams, 1991), WEPP (Flanagan *et al*., 1991), and EUROSEM (Morgan *et al*., 1992). All of these models have weather/climate components and are capable of being manipulated to predict erosion risk under different climate-change scenarios (e.g., Favis-Mortlock, 1994). Generally, increased rainfall intensity and amount, increased windspeed, and increased frequencies of high-wind events—especially if coupled with increasing droughtiness—are likely to lead to an increase in erosion. However, erosion is site-specific, and different permutations of conditions can increase or decrease it. Research has predicted erosion risk as a function of land use and environmental conditions (Nearing *et al*., 1994; Skidmore *et al*., 1994), agronomic quality (Williams *et al*., 1984), and environmental quality (Knisel, 1980; Lal, 1994a).

Despite scientific advances, the problem of accelerated soil erosion is more serious now than ever before (Lal, 1994c), and erosion hazards are being exacerbated particularly in the tropics and subtropics (Lal, 1994d). Reliable estimates of the current amounts of erosion and future areas at risk are difficult to obtain (Table 4-1; Lal, 1994b), although erosion has been suggested as affecting about 33% of the land currently used for global crop production (Brown and Young, 1990).

4.2.1. Erosion by Water

Climate change is likely to affect soil erosion by water through its effects on rainfall intensity, soil erodibility, vegetative cover, and patterns of land use. Estimates of changes in erosion risk can be made from a knowledge of projected changes in these factors. General circulation models (GCMs) can provide a range of climate scenarios, but these alone are not sufficient to predict future erosion risk, particularly because GCMs are currently poor predictors of changes in rainfall intensity and surface windspeed. In addition to more regionally reliable GCMs, accurate and reliable databases of parameters such as vegetation cover, soil properties, land use, and management

Table 4-1: *Estimates of current global rates of soil erosion and likely future trends.*

Region	Soil Erosion by Water Area[1] (10⁶ ha)	Denudation Rate[2] (mm/yr)	Dissolved Load[3] (10⁶ t/yr)	Future Trends	Soil Erosion by Wind Area[1] (10⁶ ha)	Future Trends
Africa	227	0.023	201	+	186	+
Asia	441	0.153	1592	+	222	+
South America	123	0.067	603	+	42	-
Central America	46	)	)	+	5	-
		0.055)	758)			
North America	60	)	)	+/-	35	-
Europe	114	0.032	425	+/-	42	+/-
Oceania	83	0.390	293	+	16	+
World	1094	0.079	3872	+	54.8	+

Notes: + = increased risks; - = decreased risks.
[1]Oldeman, 1991-92.
[2]Lal, 1994b.
[3]Walling, 1987.

systems are needed. These databases are important for the assessment of biophysical processes and biomass productivity (Rosenzweig *et al*., 1993) and are needed at scales appropriate to regional and global degradation processes (Bliss, 1990; Bouwman, 1990; Batjes *et al*., 1994). Such databases have not yet been developed.

GCMs indicate a marked change in soil moisture regime and, therefore, attendant changes in soil erodibility, land use, and vegetative cover. Regions likely to experience an increase in soil moisture include southern Asia (50 to 100%), South America (10 to 20%), and Oceania (10 to 20%). Regions likely to experience decreases in soil moisture include North America (10 to 50%), sub-Saharan Africa (10 to 70%), and Europe (10 to 60%) (Schneider, 1989). However, with respect to erosion, much will depend on the pattern, intensity, and seasonality of rainfall events.

A potential change in the climate might have positive effects that lead to a decrease in soil erosion risk (Sombroek, 1991–92; Brinkman and Sombroek, 1993) as a result of negative feedback mechanisms. Examples include increased biomass production, increased vegetation cover, and enhanced soil organic-matter content resulting from elevated CO_2 concentrations. However, predicted changes in temperature, rainfall, and soil moisture (IPCC, 1994) suggest that few areas will receive benefits from negative feedback effects. Instead, projected declines in levels of soil organic matter and the weakening of soil structure will make soils increasingly prone to erosion.

Modeled estimates of the effect of climate change on soil erosion depend on assumptions regarding the frequency and intensity of precipitation (Phillips *et al*., 1993). However, some estimates of future erosion have been made. For example, changes in the U.S. national average for sheet and rill erosion have been modeled under a number of different climate change scenarios. For cropped land, modeled erosion increased by 2 to 16%; in pastureland, predicted changes were -2 to +10%; and in rangeland, modeled erosion changed by -5 to +22% (Phillips *et al*., 1993). EPIC was used in the UK to show that, although an increase in temperature has little effect on erosion rate, a 15% increase in rainfall leads to a 27% increase in mean annual erosion (Favis-Mortlock *et al*., 1991; Boardman and Favis-Mortlock, 1993; Favis-Mortlock, 1994).

4.2.2. Erosion by Wind

Soil erosion occurs when wind transports soil particles by suspension, surface creep, or saltation over distances ranging from a few centimeters to many kilometers. Wind erosion not only transports soil particles around arid and semi-arid landscapes but provides inputs into ecosystems around the world and may even alter global climatic patterns. Wind erosion is particularly problematic on sandy and organic soils subject to low soil moisture, patchy vegetation, sporadic rainfall, and periodic winds. Even soils resistant to wind erosion can be blown away if the soil is damaged by trampling of animals, loosening by ploughing and tillage, pulverization by traffic (human and animal), and denudation of natural vegetation by the expansion of agriculture, excessive grazing, or fire.

Wind erosion is mainly a feature of arid and semi-arid conditions but may occur in moister zones where soil damage occurs during or just prior to periods of high wind velocity. In some areas, climate change is expected to lead to more droughty soils and less vegetation, both of which make soils more vulnerable to wind erosion (Middleton, 1985;

Hennessy *et al*., 1986). The predicted warmer climate may give rise to higher evaporation rates, leading to more frequent soil drying whether precipitation increases or not. Consequently, wind erosion may become more frequent. Although the influence of climate and human activities on wind erosion is well-documented, the feedback effect of windblown dust in the atmosphere on the warming of the upper atmospheric layers has not been thoroughly investigated (Nicholson, 1994). Desertification—an advanced result of wind erosion—is considered in Section 4.4.

4.2.3. *Mass Movement and Subterranean Erosion*

The occurrence of mass movement depends upon the interaction of various factors, including land form, lithology, soil type, rainfall intensity and duration, drainage characteristics, vegetal cover, and human intervention (Rosewell *et al*., 1991). Where sloping land is subjected to increasing rainfall of high intensity, it will become increasingly subject to mass movement.

There are various forms of subterranean erosion (Dunne, 1990), including piping (Kirkby and Morgan, 1980), intrasoil erosion, and tunnel erosion (Barrow, 1991). As with mass movement, increasing rainfall amounts and intensities will lead to increases in this form of erosion.

4.2.4. *Coastal Erosion*

The main factors affecting coastal erosion and sediment redistribution are winds, currents, tides, and floods. Rising sea level could increase coastal erosion and the loss of highly productive wetlands—and thus intensify pressure on the remaining land (see Chapter 9).

4.2.5. *Adaptive Strategies for Mitigating the Impact of Climate Change on Soil Erosion*

More than 60 years of experience are available in the development of conservation techniques and soil protection, following the U.S. Dust Bowl and similar phenomena elsewhere in the world (Kirkby and Morgan, 1980; FAO, 1983; Morgan, 1986; Schwertmann *et al*., 1989; Lal, 1990). A serious problem, however, is that many of these conservation techniques have not been adopted. Nevertheless, they are available and could be used for or adapted to changing climatic conditions. The most important requirement is that governments recognize the problem of soil erosion and set in motion the appropriate conservation mechanisms.

Future erosion risk is more likely to be influenced by increases in population density, intensive cultivation of marginal lands, and the use of resource-based and subsistence farming techniques than by changes in climate. One can anticipate that erosion, mass movement, and landslides are most likely to increase in and near regions of high population density.

4.3. Salt-Affected Soils

4.3.1. *Coastal Salinity*

Coastal salinity depends primarily on sea level and its tidal, seasonal, and long-term fluctuations; the temperature, concentration, and chemical composition of seawater; the geology, geomorphology, and relief of the coastal area, including river deltas and estuaries; and climate (temperature, precipitation, rate of evaporation, and spatial and temporal variability in them) (Jelgersma, 1988; Day and Templet, 1989; Pirazzoli, 1989; Szabolcs and Rédly, 1989; Fisher, 1990; Várallyay, 1994). The assessment and prediction of coastal salinity and salt accumulation requires comprehensive information on the hydrological, chemical, and ecological consequences of a potential rise in the eustatic sea level. Consequences include inundation of coastal lowland plains, deltas, and estuaries of big rivers; intrusion of saline seawater or brackish tidal water; rapid erosion of coastlines; a rising water table; and impeded drainage in coastal plains. In general, any rise in the eustatic sea level will result in the territorial extension of coastal salinity under the direct and indirect influences of saline seawater (Titus, 1987; Jelgersma, 1988; Szabolcs and Rédly, 1989; Hekstra, 1989; Pirazzoli, 1989; Scharpenseel *et al*., 1990; Szabolcs, 1991).

4.3.2. *Continental Salt Transport and Salt Accumulation Processes*

Impact analysis of climatic scenarios on continental salt transport and salt accumulation processes requires a much more complex approach. There are three principal mechanisms of salinization: salt accumulation, seepage, and wind deposition. Salinization by salt accumulation occurs when leaching is reduced and salt accumulates at the surface or at some depth in the soil profile—where, following erosion, it may become exposed (West *et al*., 1994). Salinization also can occur when salt is leached into a perched water table and then seeps to a lower point in the landscape (Ballantyne, 1963). Salinization by wind deposition relies on a suitable source of salt deposits. All three of these salinization processes are likely to be affected by climate change. The effects of two possible future climate scenarios—warm and dry versus warm and wet—are considered in Sections 4.3.2.1 and 4.3.2.2. Such climates are likely to show high spatial and temporal variability; various combinations of temperature and precipitation changes are likely in nature (Manabe and Holloway, 1975; Solomon *et al.,* 1987; Szabolcs and Rédly, 1989). Further variations may be caused by the physiographic variability of specific regions (agroecological unit, water catchment area, etc.) (Jelgersma, 1988; Brammer and Brinkman, 1990; Fisher, 1990; Szabolcs, 1990) and by human activities (e.g., agricultural water-management practices and water-conservation practices) (Hekstra, 1989; Szabolcs, 1989; Várallyay, 1990a, 1990b, 1990c).

4.3.2.1. *Warm and Dry Climate*

Rising temperatures during the summer will lead to higher evapotranspiration and aridity and thus higher concentration of salts in the soil solution. Where the water table is shallow, drying usually is associated with enhanced capillary rise from groundwater to overlying soil horizons. The consequences are increasing salinity in the solid and liquid phases of the soil, salt efflorescence or salt crust on the soil surface, higher salt content in the soil profile, and higher salt concentration in the soil solution. If the lowering of the groundwater table is prevented by horizontal inflow, capillary transport leads to increasing salt accumulation in the overlying soil layers. Seepage from unlined canals and reservoirs and/or filtration losses from over-irrigated or imperfectly irrigated fields will lead to horizontal groundwater inflow and/or saline seep from the surroundings to low-lying areas. These processes result in a rise of the water table due to increased capillary transport and thus to increasing salinity (Várallyay, 1968, 1994).

Higher winter temperatures have much less impact on salinity. For example, changing the ratio of rain to snow and/or having a shorter period of freezing leads to better infiltration concurrent with leaching. If the water table does rise during the temperate-zone winter, there is negligible (or no) capillary transport (because few plants are active), thus no salt accumulation (Várallyay, 1994).

4.3.2.2. Warm and Wet Climate

If the temperature increase is accompanied by a significant increase in rainfall, aridity and the concentration of salts in the soil solution will be reduced. This climatic scenario results in a net downward flow of water in the soil profile, at least for most of the year, associated with leaching, as well as a salinity reduction. However, where there is periodic drying (e.g., in a dry summer), capillary transport of salts can occur from shallow groundwater to overlying soil horizons. Thus, increased climate variability that includes periods of severe drying can lead to temporally sporadic or seasonal salt accumulation.

The accumulation of salts in soils often negatively affects soil properties and processes, including nutrient-holding capacity, nutrient dynamics, bulk density, soil structure, and porosity (see Box 4-1). Salt accumulations create extreme ecological soil environments and reduce the potential of the land for agricultural and many other uses (Kovda and Szabolcs, 1979; Szabolcs, 1990, 1991; Várallyay, 1994).

4.4. Desertification

Desertification is the process of ecological degradation by which economically productive land becomes less productive and, in extreme cases, develops a desert-like landscape incapable of sustaining the communities that once depended on it (Kassas, 1988; Westing, 1994). Desertification has aroused much emotive and scientific interest, and there are many different definitions of the term (Verstraete, 1986). The definition used in this chapter is the one adopted at the United Nations Conference on Environment and Development (UNCED) in June 1992: "...land degradation in arid, semi-arid, and dry sub-humid areas resulting from various factors including climatic variations and human activities" (UNEP, 1992; Hulme and Kelly, 1993). Desertification occurs most frequently in ecosystems that have low rainfall, long dry seasons, recurrent droughts, mobile surface deposits, skeletal soils, and sparse vegetation cover (Le Houérou, 1968; Dregne, 1983; Kassas, 1988).

Box 4-1. The Impact of Salinization on Crop Productivity in India

Soil salinity is an important chemical degradation problem for Indian agriculture, affecting 10 Mha of land—of which 2.5 Mha lie in the Indo-Gangetic Plateau. Saline soils are dominantly observed in coastal areas and in some irrigated areas inland. Sea-level rise would adversely affect the 7,000-km coastal belt of India, comprising 20 Mha of coastal ecosystem. A rise of 70 cm per century (IPCC, 1990) would inundate 25% of the coastal areas of Kerala, parts of Pondicherry, Karaikal, Tamil Nadu, and vast deltaic areas of Sundarbans (West Bengal), increasing coastal salinity and reducing crop productivity. Increased tidal ingression through creeks along the east and west coasts may further aggravate coastal salinity and damage fragile wetland ecosystems. Expected losses of soil productivity will depend on the level of sodicity but would be expected to approximate those listed in Table 4-2.

Table 4-2: *Percent loss in soil productivity.*

Exchangeable Sodium Percentage	Loss of Productivity in Alluvium-Derived Soils (Fluvisols)	Loss of Productivity in Black Soils (Vertisols)
Up to 5	nil	Up to 10
5–15	<10	10–25
15–40	10–25	25–50
>40	25–50	>50

Source: Sehgal and Abrol, 1994b.

Climate-related factors such as increased drought can lead to an increase in the vulnerability of land to desertification and to the escalation of the desertification process. In essence, desertification results from a combination of drought and mismanagement of land—in particular, the disharmony between land use and management on the one hand and the soil and prevailing climate on the other. Desertification may, in turn, affect local and global climate and thus should be viewed in a cause-effect context, as outlined by Hulme and Kelly (1993) and shown in Figure 4-1.

4.4.1. The Climatic Background of Desertification

We use the term "desert" in the sense of "true" or "climatic" desert, which is associated only with the hyper-arid zone. Desertification is a process that occurs mainly in arid to sub-humid climates that have precipitation:potential evapotranspiration (P:PET) ratios shown in Table 4-3.

The area of land occupied by these four zones in which true or induced deserts can occur is 47% of the land mass of the planet (Table 4-4).

The hyper-arid to dry sub-humid zones are subject to strong fluctuations in climate. Data from dendrochronological studies, pollen analyses, lake level surveys, glacier advances and retreats, crop distribution surveys, and grape harvesting dates confirm the occurrence of many fluctuations in the last 2,000 years.

Table 4-3: *Precipitation-to-potential evapotranspiration (P:PET) ratios of hyper-arid to sub-humid lands.*

P:PET	Regions
< 0.05	Hyper-arid (true climatic desert)
0.05–0.20	Arid (subject to desertification)
0.20–0.45	Semi-arid (subject to desertification)
0.45–0.70	Sub-humid (subject to desertification)

Regional, short-term trends or fluctuations in rainfall are a feature of semi-arid and arid lands. There has been a clear decline in rainfall in parts of Chile, where the influence of the El Niño–Southern Oscillation (ENSO) has been evident since the beginning of the century (Burgos *et al.*, 1991; Santibanez and Uribe, 1994). Rainfall in the African Sahel has failed to reach 1931–1960 mean levels in virtually all of the last 25 years. Although similar dry periods have occurred in the historical and recent geological past, there is evidence that the recent dry period in the Sahel shows more of a tendency to continental-scale dryness (Nicholson, 1994). Increasing rainfall variability

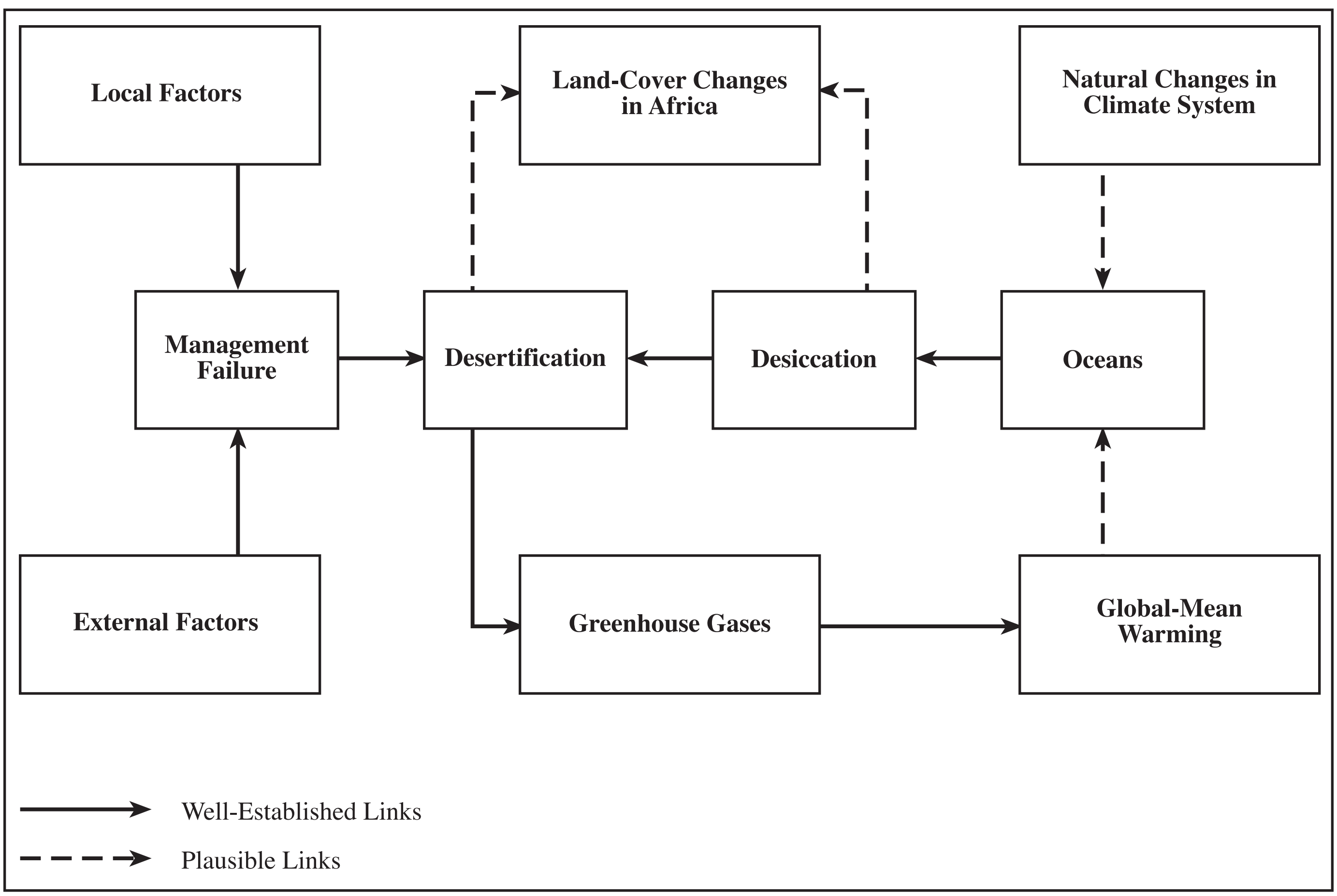

Figure 4-1: A matrix of cause and effect surrounding desertification and the role of climate change (Hulme and Kelly, 1993).

Table 4-4: *Regional distribution of world drylands (10^3 km^2) (after Oldeman et al., 1990; UNEP, 1992).*

Zone	Africa	Asia	Australasia	Europe	North America	South America	Total
Cold	0.0	1082.5	0.0	27.9	616.9	37.7	1765.0
Humid	1007.6	1224.3	218.9	622.9	838.5	1188.1	5100.4
Dry Sub-Humid	268.7	352.7	51.3	183.5	231.5	207.0	1294.7
Semi-Arid	513.8	693.4	309.0	105.2	419.4	264.5	2305.3
Arid	503.5	625.7	303.0	11.0	81.5	44.5	1569.2
Hyper-Arid	672.0	277.3	0.0	0.0	3.1	25.7	978.1
Total	2965.6	4256.0	882.2	950.5	2190.9	1767.5	13012.7

appears to be associated with this; Hulme (1992) found that there were more areas of increased variability than those of reduced variability. Highly variable conditions can trigger desertification. However, other than those areas under the influence of the ENSO and the few areas with longer-term droughts such as the Sahel, there is little evidence for recent changes in drought frequency or intensity in arid and semi-arid lands (see Chapter 3, *Observed Climate Variability and Change*, of the IPCC Working Group I volume).

Analysis of temperature data for semi-arid and arid lands by various groups presents a more confused picture than that for rainfall. For example, in Kenya there was a mean annual temperature rise of 0.4°C over the period 1942–91, perhaps tied to urbanization (Kinuthia *et al*., 1993). In South Africa, there was no temperature trend over the 1940–90 period (Mühlenbruch-Tegen, 1992). Central Asia did not see a consistent trend over 1900–1980 (Kharin, 1994); there was no trend in southern France, either (Daget, 1992). Over the last 100 years, temperature in North America increased by 0.8°C (Balling, 1994). Chapter 3 of the IPCC Working Group I volume summarizes the global surface temperature trends for the period 1920–93. The future magnitude of increases in temperature in arid and semi-arid lands is likely to be similar to or lower than the global estimate of 0.005°C per annum. The greatest increase in such lands is likely to be experienced above latitudes north and south of 40°.

Whereas most terrestrial ecosystems have some built-in ability to buffer the effects of climate variability, this is not so true of those in arid and semi-arid lands—where even small changes in climate can intensify the already high natural variability and lead to permanent degradation of the productive potential of such lands (OIES, 1991). Arid and semi-arid lands may thus be among the first regions in which ecosystem dynamics become altered by global environmental change (West *et al*., 1994).

There also is the question of the extent to which desertification itself can exacerbate climate change. It has been suggested that surface air temperature has increased significantly in desertified areas because of changes in land cover, thereby affecting global mean temperature (Balling, 1991). A reduction in surface soil moisture results in more available energy for warming the air because less is used to evaporate water. Hulme and Kelly (1993) consider this effect to be very weak but identify a better-established, though less-direct, link through the effects of changes in carbon sequestration potential and possible changes in soil conditions on emissions of nitrous oxide and methane. Hulme and Kelly (1993) point to the difficulty of quantifying the precise effect of desertification on global warming. Arid-region temperatures and rainfall should be monitored to develop a stronger information base.

4.4.2. The Nature, Causes, and Severity of Desertification

Desertification arises both from human abuse of the land and from adverse climatic conditions such as extended drought (UNEP, 1992)—which may trigger, maintain, or even accelerate the process of dryland degradation. Currently there is disagreement as to whether human impacts or climatic factors are the primary agents responsible for the desertification of the world's arid and semi-arid lands.

Some evidence suggests that human impacts arising from overstocking, overcultivation, and deforestation are primarily responsible for the process. Such conclusions have been reached by scientists working in northwest China (Chao Sung Chiao, 1984a, 1984b); Australia (Perry, 1977; Mabbut, 1978); South America (Soriano, 1983); North America (Dregne, 1983; Schlesinger *et al*., 1990); Europe (Lopez-Bermudez *et al*., 1984; Rubio, 1987; Katsoulis and Tsangaris, 1994; Puigdefabregas and Aguilera, 1994; Quine *et al*., 1994); North and West Africa and the Sahel (Pabot, 1962; Le Houérou, 1968, 1976, 1979; Depierre and Gillet, 1971; Boudet, 1972; Lamprey, 1988; Nickling and Wolfe, 1994; Westing, 1994); East Africa (Lusigi, 1981; Muturi, 1994); and South Africa (Acocks, 1952; Hoffman and Cowling, 1990a; Bond *et al*., 1994; Dean and McDonald, 1994). Many of these studies suggest that, although desertification is the result of a complex interaction of a number of factors, the direct causes are human actions—which themselves are a function of population density (see Figure 4-2), cultural traditions, land tenure, and other socioeconomic and political factors. Although climate and soil type are important in determining the severity and rate of desertification, it is ignorance or the force of circumstance in

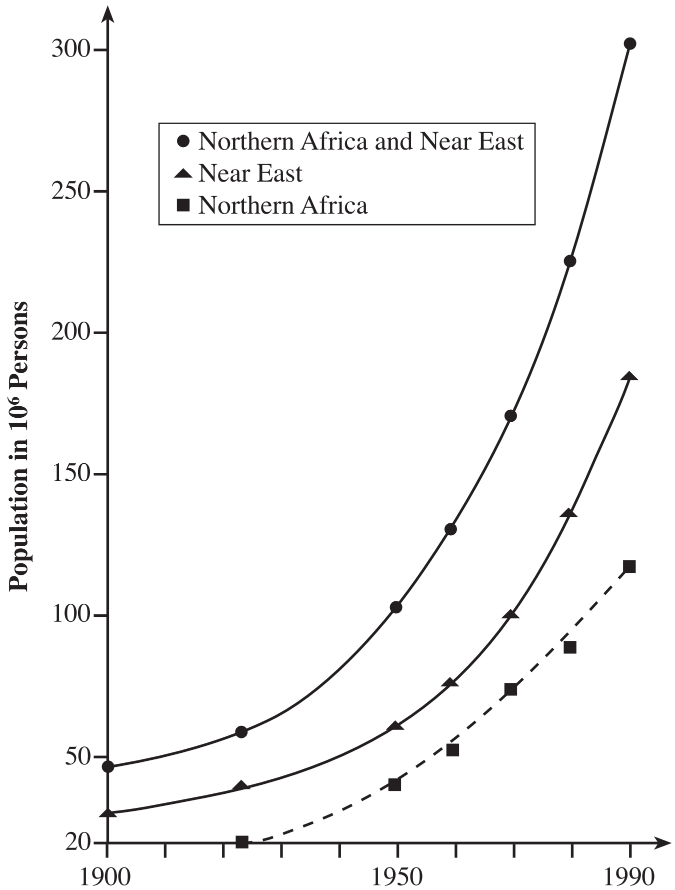

Figure 4-2: Evolution of the human population in northern Africa and the Near East from 1900 to 1990. Sources are various, including FAO yearbooks (Le Houérou, 1992).

failing to match the use and management of the land to the soil and prevailing climate that leads to the removal of soil. Overstocking, deforestation, wood collection, and overcultivation usually are cited as the principal direct causes of the problem; estimates of the percentage of desertified land attributed to each of these factors are available (Table 4-5).

However, a somewhat different view of the causes of desertification also exists. For some Asian environments (e.g., Singh *et al.*, 1994) and particularly in African environments, there is a growing body of literature that emphasizes the impact of extended droughts over the last several decades in the desertification process or suggests that desertification has been overstated due to a lack of adequate information (Hellden, 1988, 1991; De Waal, 1989; Forse, 1989; Mortimore, 1989; Binns, 1990; Hoffman and Cowling, 1990b; Tucker *et al.*, 1991; Grainger, 1992; Thomas, 1993; Dodd, 1994; Pearce, 1994; Thomas and Middleton, 1994). Proponents of this view argue that domestic livestock populations seldom build up to numbers that are damaging for these environments because the periodic droughts that characterize these regions frequently result in high animal mortality (see Behnke *et al.*, 1993; Dodd, 1994; Scoones, 1995).

There also is a great deal of variation in assessments of the nature and severity of the desertification problem, due mainly to the lack of adequate data. Some researchers suggest that almost 20 million km^2 (15% of the land surface of the Earth) are subject to various degrees of desertification; they provide estimates of the extent and severity of the problem for different regions (Dregne, 1983, 1986; Le Houérou, 1992; Table 4-6). In addition, there have been a number of attempts to calculate the rate of expansion of the more arid regions into the more mesic areas. Most of these studies have employed remote sensing, notably with air photos and large-scale satellite images (e.g., SPOT) taken decades apart, combined with detailed maps of ground-control and older vegetation, forest, or range resources. Many of these large-scale studies have suggested that the annual rate of expansion of desertified lands in central Asia, northwest China, northern Africa, and the Sahel ranges from 0.5 to 0.7% of the arid zone (Le Houérou, 1968, 1979, 1989, 1992; Depierre and Gillet, 1971; Boudet, 1972; De Wispelaere, 1980; Gaston, 1981; Haywood, 1981; Floret and Pontainier, 1982; Chao Sung Chiao, 1984b; Peyre de Fabrègues, 1985; Vinogradov and Kulin, 1987; Grouzis, 1988; Rozanov, 1990). Assuming a conservative rate of expansion of 0.5% per annum, this information has been used to suggest an annual increment of desertified land of 80,000 km^2 (see also Hulme and Kelly, 1993). Because 25% of the arid zone already is desertified, this estimate would mean that almost all of the world's arid and semi-arid lands will become desertified within the next century if rates of desert expansion are similar to those that have prevailed over the past 50 years. Complete arid-land desertification could occur earlier if human and livestock populations continue to increase and particularly if the resilience of arid regions is negatively affected by climate change (Hulme and Kelly, 1993).

Table 4-5: *Causes of desertification, in percent of desertified land (after Le Houérou, 1992).*

Regions or Countries	Overcultivation	Overstocking	Fuel and Wood Collection	Salinization	Urbanization	Other
Northwest China	45	16	18	2	3	16
North Africa and Near East	50	26	21	2	1	–
Sahel and East Africa	25	65	10	–	–	–
Middle Asia	10	62	–	9	10	9
United States	22	73	–	5	–	–
Australia	20	75	–	2	1	2

Table 4-6: *Extent and severity of desertification (after Oldeman et al., 1990; Le Houérou, 1992; Le Houérou et al., 1993; UNEP, 1992).*

	Light		**Moderate**		**Strong**		**Severe**	
Region	Area	%	Area	%	Area	%	Area	%
Africa	1180	9	1272	10	707	5.0	35	0.2
Asia	1567	9	1701	10	430	3.0	5	0.1
Australasia	836	13	24	4	11	0.2	4	0.1
North America	134	2	588	8	73	0.1	0	0.0
South America	418	8	311	6	62	1.2	0	0.0
Total	4273	8	4703	9	1301	2.5	75	0.1

Notes: Area desertified in 10^3 km^2; % = area desertified in percent of total drylands; drylands = arid + semi-arid + dry sub-humid.

Some recent research, however, has not supported the expanding-desert hypothesis. First, a number of researchers question the data upon which the severity estimates (see Table 4-6) are based (Hellden, 1988; Thomas, 1993; Dodd, 1994). Second, some argue that the process cannot be accurately described as a degradation front that grows incrementally larger each year. Arid and semi-arid systems are characterized by variable climates subject to large fluctuations in annual rainfall. During favorable or "wet" years there is little evidence to suggest that the desertification front expands (Thomas, 1993). On the contrary, a number of recent studies suggest that vegetation cover at the margins of arid and semi-arid regions both increases and decreases, depending largely on seasonal and annual rainfall totals (Hoffman and Cowling, 1990b; Tucker *et al*., 1991). The different views regarding the importance of human abuse versus adverse climatic conditions in causing desertification, and the lack of agreement on the scale of the problem, point to the need for a better understanding of the problem and, in particular, better and more comprehensive data on its nature and extent. There is little doubt that desertification is an important environmental problem that needs to be addressed urgently—and that climate change will have an impact on it.

4.4.3. The Impact of Drought and Desertification on Natural Ecosystems and Rain-Fed Crops

The impact of drought on natural ecosystems is measured by plant cover and biomass production and by the disruption of food production systems (De Waal, 1989; Mortimore, 1989). Drought reduces the number, phytomass, and ground cover of plants and hence reduces the protection of the soil against erosion (Grainger, 1992). Desertification has much more profound and lasting effects. Desertified soils are subject to extensive water and wind erosion and therefore lose much of their depth and ability to store water and nutrients (Mainguet, 1986; Grainger, 1992). In the worst cases, all perennials are removed, and the soil surface is subjected to large-scale wind and water erosion. Without permanent vegetation protection, the soil surface is eroded by running water, sealed and crusted by raindrop splash, and made increasingly impervious and hence prone to more erosion. Soil surface sealing and encrustation reduces water intake, resulting in a drier environment. Thus, a whole spiral of self-perpetuating edaphic aridity is triggered (Le Houérou, 1969; Floret and Pontainier, 1984). Eventually, all of the soft soil layers are removed, and the situation becomes irreversible.

Schlesinger *et al*. (1990) propose that not only does drought and the loss of vegetation cover lead to desertification, but a mere shift in plant growth form dominance, as a consequence of overgrazing, may drastically reduce productivity. In their model of dryland degradation in the southwestern United States, they suggest that overgrazing results in the redistribution of organic matter and nutrients and is the primary agent responsible for the current conversion of previously productive grasslands to unproductive mesquite (*Prosopis glandulosa*) shrublands. Where resources within semi-arid grasslands previously were homogeneously distributed, overgrazing results in their concentration beneath shrub islands. Not only is the productivity of the land reduced, but positive feedback processes render the changes irreversible (Schlesinger *et al*., 1990).

Rangelands are likely to be prone to desertification because of their inherent fragility (see Chapter 2). Hanson *et al*. (1993) use three GCMs to assess the effect of climate change on plant and animal production in the Great Plains of North America. Their scenarios predict decreases in plant nitrogen content during summer grazing and decreases in animal production because of increased ambient temperature and decreased forage quality. Using a 1-year time-step livestock-production model, they show for the simulations used that carrying capacities would need to drop from above 6.5/ha to 9/ha to maintain 90% confidence of not overstocking.

Desertification causes soil to lose its ability to support rain-fed crops (El-Karouri, 1986). It inevitably results in emigration as the land cannot sustain the original inhabitants (Westing, 1994). There are indications that as much as 3% of the African population has been permanently displaced, largely as a result of environmental degradation.

4.4.4. Adaptive Strategies for Mitigating the Impacts of Climate Change on Desertification

As we have noted, some desertification already is irreversible. Many other examples of desertification are reversible given appropriate legislation, technology, conservation techniques, education, and, most importantly, the will to act. There are various measures to combat the aridity that might lead to desertification. The impact of increased aridity on natural ecosystems and crops would be moderate and in most cases manageable if improved agricultural and management practices—such as the selection of more drought-tolerant species and cultivars, shorter-cycle annual crops, better tillage practices, soil conservation practices, more timely agricultural operations, and more water-conserving crop rotations—were adopted. In natural ecosystems such as rangelands, increased aridity could be mitigated through the use of more appropriate stocking rates and more balanced grazing systems such as deferred grazing, the concurrent utilization of various kinds of stock species and breeds, game ranching, mixed stock and game ranching, commercial hunting, and so forth.

4.4.4.1. *Water Use and Management*

One of the primary factors affecting water availability is the annual distribution of precipitation. There are large differences in water availability in soils within a given land system or landscape, depending on topography, geomorphology, and the nature of the soil and its depth. Many surveys show that water availability in contiguous soils may vary by a factor of one to ten or more (Le Houérou, 1962; Floret and Pontainier, 1982, 1984). The actual distribution of water in soils may be modified considerably by tillage and mulching practices, soil and water conservation techniques, runoff farming, water harvesting, and wadi diversion. Most of these techniques have been known for nearly 3,000 years in the Near and Middle East.

The techniques of runoff farming—which probably date to nearly 3,000 years ago in western China, Iran, Saudi Arabia, Yemen, Jordan, northern Africa, and Spain—have hardly been used outside their own regions but are capable of development elsewhere. Unfortunately, some of these techniques are being abandoned in countries in which they have been in use for centuries, such as southern Tunisia, Libya, northern Egypt, Yemen, and Iran. The techniques of water harvesting—well-developed in the Near East and North Africa during Roman and Byzantine periods (200 BC to 650 AD)—could be developed again within and outside these regions taking care to ensure that the new conditions are suitable for them.

Irrigated farming may not suffer from increased aridity even if water availability becomes more difficult. Improved irrigation practices (e.g., generalized drip irrigation, underground irrigation) can save up to 50% water compared with conventional irrigation systems. Under more-arid future conditions, one could expect a very large increase in the use of irrigation, in addition to the expansion of controlled farming, crop genetic improvement, and the expansion of winter-growing crops that are much less demanding on water.

In most arid and semi-arid countries, wasted water is common, particularly in agriculture (due to inefficient irrigation systems). The amount of waste commonly reaches 50% in many countries, but such waste often is easy to prevent with appropriate techniques. In many countries, water from aquifers (both shallow and deep) is being used at rates that exceed recharge. Increased pumping of water from these aquifers for irrigation will hasten their depletion and threaten the availability of this water for even more vital needs. Future development in many countries will require water savings.

Two ways to save water besides improved irrigation and drainage systems are to utilize water-efficient plants and to develop winter-growing crops. Alfalfa, for instance (a very popular fodder crop), is extremely water-demanding—requiring about 700–1000 kg of water to produce 1 kg of fodder dry matter—whereas some other fodder crops are less water-demanding for the same yield. Winter-growing crops consume much less water than summer crops because PET during winter is only a small fraction of the summer amount.

Drainage water, which has a rather high concentration of salts, can be re-used to grow salt-tolerant crops, including cashcrops such as asparagus or industrial crops such as sugar beet; it also may be used to grow timber and fodder. Some timber and fuelwood species can produce high yields with water having half the salt concentration of seawater, as can a number of fodder crops such as saltbushes, fleshy sainfoin, tall fescue, and strawberry clover (Le Houérou, 1986). There is, however, a potentially detrimental effect of re-using salt-enriched drainage waters—namely, the accelerating salinization of soil, as occurred adjacent to the Nile in Egypt.

There are many techniques that could be used to counteract a moderate increase in climatic aridity, such as those outlined above, but these techniques tend to increase the costs of production and thus alter the conditions of commercial competition of products on the markets.

4.4.4.2. *Land-Use Systems*

Adaptation to drought and desertification has challenged pastoralists, ranchers, and farmers for centuries. Pastoralists and ranchers have drought-evading strategies and farmers have drought-enduring strategies. Drought-enduring strategies include the adoption of a light stocking rate that preserves the dynamics of the ecosystems and their ability to recover after drought, and the utilization of agroforestry techniques whereby fodder shrubs and trees that can store large amounts of feed over long periods of time are planted in strategic locations in order to provide an extra source of feed when drought occurs. Among the species used are saltbush plantation, spineless fodder cacti (*Agave americana*), wattles (*Racosperma* spp), mesquites (*Prosopis* spp), and acacias (*Acacia* spp). These provide and thus encourage a more permanent rather than nomadic existence even when the range is dry and parched.

Another drought-enduring strategy utilized in the United States and South Africa is game ranching of animals that are better adapted to dry conditions than are livestock—including several species of Cervidae, various antelopes, and ostriches. There are at present more than 20 Mha of game ranching in South Africa, Namibia, Botswana, and Zimbabwe (Le Houérou, 1994). The utilization of stock species and breeds that are better adapted to dry conditions is a further possible adaptation. Many East African pastoralists (Somali, Rendille, Gabra, Samburu) have shifted recently from cattle-husbandry to camel-rearing as a response to the deterioration of their environment; others have increased the proportion of goats compared to sheep (e.g., Turkana).

A drought-evading approach to coping with drought and desertification is the application of soil-conservation techniques, including zero or minimum tillage, contour furrowing, pitting, banking, terracing, and benching. Most of these techniques have been known to some ethnic groups and to some regions for a long time, yet they have rarely been extended outside their region of origin.

The overall strategy should be the development of diversified and multiple production systems—including wildlife, combined with livestock and game ranching; commercial hunting; various tourism activities, including so-called green-tourism; runoff farming; poultry production; and nonagricultural activities such as handicraft. Such activities are developed to various levels in a number of countries, such as the drylands of the United States (west of 100° longitude), Australia, South Africa, Namibia, Botswana, Zimbabwe, Kenya, and Tanzania. There is no reason why these practices could not be developed elsewhere.

4.4.4.3. Agroforestry

Agroforestry may play an extremely important role in the development of semi-arid and arid lands and in the struggle against desertification (Le Houérou, 1980; Baumer, 1987; Le Houérou and Pontainier, 1987). Agroforestry techniques have been developed for centuries in some rural civilizations—such as Kejri [*Prosopis cineraria* (L) Druce] in northwest India (Rajasthan); *Faidherbia albida* (Del.) Chev. in various parts of intertropical Africa; saltbushes in various arid zones of the world; *Argania spinosa* (L.) Sk in southwest Morocco; *Quercus ilex* L. and *Q. suber* L. in Spain and Portugal; and Espino *(Acacia caven* Mol.) and Algarrobo *(Prosopis spp*) in Latin America. Such techniques permit high rural population densities in arid zones (e.g., 60–80 people/km^2) with *Faidherbia* in southern Sahel, and similar densities in Rajasthan with *Prosopis cineraria* and in southern Morocco with *Argania* (the latter region receives <150–300 mm/yr rainfall).

Agroforestry therefore should be an integral part of any dryland development strategy for sustainable agriculture. This development should include village woodlots, which—when located in strategic situations on deep soils, and benefiting from some runoff—may produce very high yields as long as the right species of tree are selected and then rationally managed. Such woodlots could and should be an important part of the fight against desertification because fuelwood collection is a major cause of land degradation in many developing countries.

4.4.4.4. Conservation and Biodiversity

The world's semi-arid and arid lands contain a large number of species of plants and animals that are important to humankind as a whole. Due to recent desertification of several regions of the world, many species are endangered or will soon be. The only way to preserve this biological capital for the benefit of humankind is *in situ* conservation projects. However, conservation is expensive, particularly in areas where the demand on the land is acute because of high human population growth.

4.5. Other Forms of Soil Degradation

There are a number of other soil processes that can lead to land degradation under a changing climate. For example, organic-matter levels may decline; leaching may increase, giving rise to loss of nutrients and accelerated acidification; and, in some instances, soil structure may deteriorate. Some of these changes already are taking place as a result of land-use changes, poor farming practices, and industrial emissions. To date, the changes are fairly subtle, and increasing slowly—unlike some forms of erosion and salinization which can occur more quickly.

4.5.1. Declining Organic-Matter Levels

Organic matter probably is the most important component of soils. It influences soil stability, susceptibility to erosion, soil structure, water-holding capacity, oxygen-holding capacity, and nutrient storage and turnover, and it provides a habitat for extremely large numbers of soil fauna and microflora. With the expansion of agriculture and its intensification, soil organic-matter levels have declined. In the United States, for example, many prairie soils have lost more than one-third of their initial organic-matter contents after 100 years or more of cultivation (Papendick, 1994).

A decline of 55–58% in organic matter (equivalent to a loss of 29–32 t/ha) has been noted in the top 10 cm of two alluvial soils in New Zealand after just 2 years of continuous cropping (Shepherd, 1992). Much of this organic matter was lost to the atmosphere as CO_2; this demonstrates the point that some intensively cropped land can potentially release a significant amount of greenhouse gases (Tate, 1992).

Organic matter is susceptible to change with changing climate. Higher temperatures increase rates of decomposition. Whether enhanced atmospheric CO_2 concentrations will give rise to sufficient increases in plant growth to return organic matter to soils and compensate for this loss is still not established (see Chapter A). If CO_2 levels do not lead to compensation, it will be important to implement programs of organic-matter management to maintain adequate soil organic-carbon contents to prevent degradation. This also will benefit carbon sequestration (see Chapters 23 and 24).

4.5.2. Declining Nutrient Levels

Loss of nutrients is a common phenomenon in countries with low-input agriculture and also occurs under soils with a high leaching potential and a low buffering capacity.

In soils in which the movement of water is predominantly downward, there will be a tendency for nutrients to be lost. In intensive, high-input agriculture, such losses are compensated by fertilizer additions, but under low-input agriculture, loss of nutrients is a common occurrence—one that is recognized as an increasing problem, particularly in subtropical and tropical countries (Smaling, 1990; Pereira, 1993).

Temperature and precipitation changes could affect soil nutrient levels in several ways. Rising temperatures could act to maintain nutrients within the soil because of increased evaporative forces, and thus reduce leaching. An increase in rainfall generally will give rise to increased nutrient loss. Conversely, a decrease in rainfall may lead to upward movement of nutrients—which, in some cases, can lead to salinization (see Section 4.3). Nutrient loss can be compensated by the use of inorganic and organic fertilizers, but the cost can be prohibitive for subsistence farmers.

4.5.3. Acidification

Most countries contain large areas of acidified soils (Wild, 1993). The extent to which acidification will increase with climate change depends on both rainfall and temperature. Significant increases in rainfall would be accompanied by increased leaching and thus acidification (Rounsevell and Loveland, 1992). A decline in rainfall could reduce the extent and intensity of acidification. In the sub-arid and sub-humid zones, soils are subject to seasonal changes—from leaching conditions to evaporative conditions. An altered climate could shift conditions to a dominantly leaching regime involving increased acidification, or to a dominantly evaporative regime involving less acidification but possible salinization. The direction of change will depend on the extent to which rainfall and temperature change.

One of the soil types most affected by acidification is termed acid sulfate soils. These soils suffer from extreme acidity as a result of the oxidation of pyrite when pyrite-rich parent materials are drained (Dent, 1986). Pyrite accumulates in waterlogged soils that are rich in organic matter and contain dissolved sulfates, usually from seawater. When these previously waterlogged soils are drained, oxygen enters the soil system and oxidizes pyrite to sulfuric acid, causing the pH to drop to less than 4.

Several areas of the world contain potential acid sulfate soils, which would be converted to acid sulfate soils if climate change were to lead to the lowering of water tables and increased oxidation (in total over 20 Mha; Beek *et al*., 1980). The principal areas affected would be coastal areas of West Africa, South America, India, and the Far East.

4.5.4. Deterioration of Soil Structure

Soil structure regulates water retention and movement, nutrient transformations and movement, faunal activity and species diversity, and the strength and penetrability of the rooting media (Lal, 1994a). Soil structure affects the ability of the soil to be cultivated, and the quality and durability of seedbeds—and thus plant growth and vigor, grain yield, and grain quality (Shepherd, 1992). The potential for deterioration of soil structure as a result of climate change, in conjunction with poor soil management, has received little attention from the scientific community even though soil structure controls water and air movement and transport processes in the soil profile. Changes to soil structure are notoriously difficult to quantify, partly because of the influence of land use and management; research needs to be directed toward a better understanding of this. However, some potential consequences of climate change can be identified.

A decline in soil organic-matter contents as a result of climate change has important implications for soil quality in general and specifically for soil structural development because there is a strong relationship between organic-matter levels and soil structure quality (see Chapter A). A decline in soil organic-matter levels would cause a decrease in soil aggregate stability, an increase in susceptibility to compaction, lower infiltration rates, increased runoff, and, hence, enhanced likelihood of erosion.

A second important function of soil structure—in relation to clay soils particularly—is their influence on water quality and seepage. Soils with high clay contents, especially those with expanding type clays (smectitic mineralogy), tend to shrink when they are dry and swell as they wet-up again. This behavior results in the formation of large cracks and fissures. Drier climatic conditions would be expected to increase the frequency and size of crack formation in soils, especially those in temperate regions that currently do not reach their full shrinkage potential (Climate Change Impacts Review Group, 1991). One consequence would be more rapid and direct movement of water and dissolved solutes from soil to surface waters or aquifers through so-called "bypass" flow via cracks (Armstrong *et al*., 1994). The more direct movement of water in this way would decrease the filtering capacity of soil and increase the possibility of nutrient losses and pollution of ground and surface waters. Where animal manures or sewage sludge are applied to land, there would be a greater risk of organic contaminants and microorganisms reaching aquifers.

In the case of acid soils, increased cracking could lead to an increase in the quantity of metals (e.g., aluminum, manganese, iron, heavy metals) entering aquifers. In these situations, the combined effects of changes in soil chemical and biological cycles and increased cracking need to be assessed (Rounsevell and Loveland, 1992). An additional consequence is that the soil profile would not re-wet as before, and the rooting zone could be deprived of valuable water. Such changes also would have important implications for the stability of the foundations of buildings and roads—which would have been designed on the basis that such soils did not reach their shrink-swell capacity (Boden and Driscoll, 1987).

4.6. Monitoring and Research Needs

4.6.1. Monitoring

Global estimates of land degradation generally are very crude; as a result, it is difficult to present a meaningful picture of its extent and severity. The most recent attempt by Oldeman *et al.* (1990) helps to indicate the types and severity of land degradation, but because of a lack of adequately established national surveys or a global network of monitoring sites, the results can only be a broad approximation. Compared with air and water, soil has received little attention in terms of monitoring; very few countries have sound data on the quality of their soils, and there often are few or no trend data to indicate whether or how soil quality is changing. There is a need to establish a comprehensive monitoring system for soil quality at a national level that will contribute to the creation of a global picture. In the absence of such a program, there will be general ignorance of changes in soil quality with time, leading to an inability to address strategically any deleterious changes. The limited information that is available suggests that land degradation is a major global problem that urgently needs to be addressed.

4.6.2. Research

To date, most research on the impacts of climate change on soils has involved taking knowledge of soil processes and properties gained over some 50 years and predicting what effect a new climatic scenario might have on them. Other research has examined the impacts of climate change on soils in terms of their ability to support current and future crops and natural ecosystems. Both of these approaches, although justifiable on the basis of the need for early predictions of the effects of climate change, often lack rigor.

There are three areas in which research now needs to focus:

- Determining the impact of increased atmospheric CO_2 concentrations, temperature, and changes in other climatic parameters on soil properties and processes, including those involved in land degradation under different land uses in different climatic zones
- Identifying the impact of these climate-induced changes on soil processes and properties and on the ability of the soil to perform its functions (e.g., as a habitat for microflora and fauna, nutrient storage and turnover, water storage and movement)
- Understanding how such changes will affect terrestrial ecosystems, what the response times of such systems to soil changes will be, and what the suitability of changed soils will be for crops and more natural habitats.

A successful outcome to this research requires continuing improvements to terrestrial nutrient-cycle models and GCMs. In particular, much better information is required for rainfall—including amount, frequency, duration, and intensity—and for surface wind, including direction, speed, and frequency of high-wind events. Given improved model output that is more reliable at the regional scale and the research outlined above, governments and land managers will receive increasingly valuable indicators of future conditions.

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